HYDRAULIC GRAVITY RAM PUMP

BACKGROUND OF THE INVENTION

[0001] This invention relates to pumps, and in particular to piston type pumps for pumping liquids to significantly higher elevations and pumps having energy recovery means.

[0002] Pumping liquids against substantial hydraulic heads is a problem encountered in pumping out mines, deep wells, and similar applications such as pumping water back up, over a hydro dam during low energy usage periods, for subsequent recovery during high energy usage periods, and for use in run-of-the-river hydro power applications utilizing the potential energy of water in a standing column .

[0003] A number of earlier patents attempt to provide devices which utilize a piston type pump where energy is recovered from a column of liquid acting downwardly on the piston, as the piston moves downwardly, in order to assist in subsequently raising the piston together with a volume of liquid to be pumped upwardly. An example of such an earlier patent is United States Patent No. 6,193,476 to Sweeney. However such earlier devices have not been efficient enough to justify their commercial usage. For example, in the Sweeney patent, the efficiency of the apparatus is significantly reduced due to the fact that the upper piston 38 has the same cross-sectional area as lower piston 43. Thus the pressure of liquid acting upwardly on the lower piston 43 inhibits downward movement of the upper piston 38 under the weight of the liquid in the cylinder above.

[0004] It is an object to the invention to provide an improved pumping apparatus capable of pumping liquids against significant hydraulic heads, such as encountered in deep wells or in pumping out mines, without requiring pumps with high output heads.

[0005] It is a further object of the invention to provide an improved piston type pumping apparatus with provision for energy recovery, having significantly improved efficiency

compared with prior art devices of the general type as well as the ability to use the potential energy of a standing column.

[0006] It is still further object of the invention to provide an improved piston type pumping apparatus which is simple and rugged in construction, and efficient to operate and install.

SUMMARY OF THE INVENTION

[0007] According to the invention there is provided a piston type pumping apparatus, comprising a vertically oriented cylinder having a top and a bottom with a first passageway for liquid in the cylinder adjacent to the top thereof. There is a second passageway for liquid in the cylinder adjacent to the bottom thereof. A piston is reciprocatingly mounted within the cylinder. The piston has an area against which pressure acts in the direction of movement of the piston. A hollow piston rod is connected to the piston and extends slidably and sealingly through an aperture in the bottom of the cylinder. There is a reload chamber below the cylinder, the piston rod extending slidably and sealingly into the reload chamber and having a third passageway for liquid communicating with the reload chamber. The piston rod has a smaller area within the reload chamber upon which pressurized fluid in the reload chamber acts in a direction of movement of the piston and piston rod, compared to the area of the piston, whereby liquid in the cylinder acting downwardly on the piston exerts a greater force on the piston than liquid in the reload chamber acting against the piston rod. There is a first one-way valve located in the third passageway which permits liquid to flow from the reload chamber into the piston rod and prevents liquid from flowing from the piston rod into the reload chamber. A fourth passageway for liquid extends from the reload chamber to a source of liquid to be pumped. A second one-way valve in the fourth passageway permits liquid to flow from the source of liquid into the reload chamber and prevents liquid from flowing from the reload chamber towards the source of liquid. There is means for storing pressurized liquid connected to the second passageway for storing pressurized liquid displaced from below the piston, as the piston moves downwardly, and

to assist in raising the piston and, accordingly, liquid contained within the piston rod, to pump liquid upwardly and through the first passageway.

[0008] For example, the means for storing may include a pressurized body of liquid.

[0009] There may be a pump connected to the body of liquid for pumping liquid into the cylinder below the piston to raise the piston.

[0010] In one example the pump is a piston pump. The body of liquid may be a vertical column of liquid.

[0011] In another example, the pump may be a rotary pump and the means for storing may include a receiver for pressurized liquid connected to the pump.

[0012] The invention offers significant advantages compared with conventional pumps for deep wells, pumping out mines and other applications for pumping liquids up relatively high hydraulic heads, such as energy recovery at hydro dams. It allows the use of a pump which requires far less energy input to pump liquids up significant vertical distances because it converts the potential energy of the standing column into kinetic energy. At the same time, it overcomes disadvantages associated with prior art pumps of the general type by increasing its efficiency significantly by comparison. Thus the invention is attractive for commercial applications where prior art devices have not proven to be viable.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] In the drawings:

Figure 1 is a simplified elevational view, partly in section, of a pumping apparatus according to an embodiment of the invention;

Figure 2 is a simplified elevational view, partly in section, of the upper fragment of an alternative embodiment employing a centrifugal pump;

Figure 3 is a graph of the efficiency of the pressure head concept of the pump;

Figure 4 is a sectional view of the embodiment of Figure 1 showing the Force Balance in the pump;

Figures 5a and 5b are simplified sectional views showing Pressure Head Concept of a pump and the Power Cylinder Concept of the pump.

DETAILED DESCRIPTIONS OF THE PREFERRED EMBODIMENTS

[0014] Referring to the drawings, and first to Figure 1, this shows a piston type pumping apparatus 20 according to an embodiment of the invention. The apparatus is intended to pump liquids, typically water, up relatively great vertical distances, such as from the bottom of a mine to the surface as exemplified by the distance between points 22 and 24. The system includes a vertically oriented first transfer cylinder 26 having a top 28, adjacent point 24, and a bottom 30. There is a first passageway 32 for liquid adjacent the top where liquid is discharged from the cylinder. There is a second passageway 34 near the bottom of the cylinder which allows liquid to enter or exit the cylinder.

[0015] A transfer piston 40 is reciprocatingly mounted within the cylinder and is connected to a vertically oriented, hollow piston rod 42 which extends slidably and sealingly through aperture 44 in the bottom of the cylinder. The piston 40 has an area 29 at the top thereof against which pressurized fluid in the cylinder acts. The passageway 32 is above or adjacent to the uppermost position of the piston and the passageway 34 is below its lowermost position. It should be understood that Figure 1 is a simplified drawing of the invention and seals and other conventional elements which would be apparent to someone skilled in the

art are omitted. These components would be similar to those disclosed in United States Patent No. 6,913,476 which is incorporated herein by reference.

[0016] There is a first one-way valve 41 at the bottom of the piston rod 42 which includes a valve member 43 and a valve seat 45 which extends about a third passageway 47 in bottom 49 of the piston rod. This one-way valve allows liquid to flow into the piston rod, but prevents a reverse flow out the bottom of the piston rod.

[0017] There is a reload chamber 46 below the cylinder 26 which is sealed, apart from aperture 48 at top 50 thereof, which slidably and sealingly receives piston rod 42, and fourth passageway 52 at bottom 54 thereof. The piston rod acts as a piston within the reload chamber. There could be a piston member on the end of the rod within the reload chamber and the term "piston rod" includes this possibility. A second one-way valve 56 is located at the passageway 52 and includes a valve member in the form of ball 58 and a valve seat 60 adjacent to the bottom of the reload chamber. There is an annular stop 62 which limits upward movement of the ball. This one-way valve allows liquid to flow from a source chamber 70 into the reload chamber 46, but prevents liquid from flowing from the reload chamber towards the chamber 70. Chamber 70 contains liquid to be pumped out of passageway 32 at top of the cylinder.

[0018] The piston 40 has a diameter D1 which is substantially greater than diameter D2 of the piston rod and, accordingly, the piston rod, acting as a piston in the reload chamber, has a significantly smaller area upon which pressurized liquid acts, in the direction of movement of the piston rod and piston 40, within the reload chamber 46 compared to the cross-sectional area of the piston 40 and the interior of cylinder 26. For example, in one embodiment the piston is 3" in diameter, while the piston rod 42 is 1" in diameter. Therefore liquid in the cylinder at a given pressure exerts a much greater force on the piston and piston rod compared to the force exerted upwardly on the piston rod and piston by a similar pressure of liquid in reload chamber 70.

[0019] There is means 80 for storing pressurized liquid 82 connected to the second passageway 34. This means 80 stores pressurized liquid recovered from chamber 90 in the cylinder 26 below the piston 40. In this particular embodiment the means includes a column of liquid 92 extending from passageway 34 to a point 94 at the top of the column. The column in this example is formed by an annular jacket 96 extending about the cylinder 26 and a conduit 98 extending to discharge end 100 of a second, power cylinder 102. The column can be pressurized by a remotely located power cylinder or by using a body of liquid (water), located at a higher elevation, as a pressure head.

[0020] The cylinder 102 has a piston 104 reciprocatingly mounted therein. The liquid 82 occupies chamber 106 on side 108 of the piston which faces discharge end 100 of the cylinder. Chamber 110 on the opposite side of the piston is vented to atmosphere through passageway 112. There is a piston rod 114 connected to the piston 104 to drive the piston towards the discharge end and thereby discharge liquid 82 from the cylinder.

[0021] In operation, the cylinder 26 is filled with liquid, typically water, above the piston 40. Likewise chamber 90 is filled with water along with the jacket 96 and chamber 106 of the second cylinder 102. Similarly piston rod 42 is filled with water or other liquid along with the reload chamber 46 and the source chamber 70. The piston is in the lowermost position as shown in Figure 1. This is required to prime the pump.

[0022] The piston rod 114 is then moved to the left, from the point of view of Figure 1, typically by a motor or engine with a crank mechanism or a pneumatic or hydraulic device, although this could be done in other ways. This displaces liquid 82 from the cylinder 102 downwardly through the column 92, through the second passageway 34 into the chamber 90 where it acts upwardly against the bottom of piston 40 and pushes the piston upwards in the cylinder 26.

[0023] The piston rod 42 is pushed upwardly along with the piston and thereby reduces pressure in reload chamber 46, since the volume occupied by the piston rod in the reload

chamber is reduced as the piston rod moves upwardly. One-way valve 41 prevents liquid from flowing from the piston rod into the reload chamber, but the reduced pressure within the reload chamber causes ball 58 to rise off of its seat 60, such that liquid flows from chamber 70 into the reload chamber.

[0024] When piston 104 of the cylinder 102 approaches the end of its travel adjacent discharge end 100, and piston 40 approaches its uppermost position towards top 28 of the cylinder 26, liquid is discharged from the passageway 32. When the piston 104 has reached its limit adjacent discharge end 100, pressure against piston rod 114 is released. The weight of liquid occupying cylinder 26 above the piston 40 acts downwardly on the piston and forces the piston towards its lowermost position shown in Figure 1. This forces liquid out of chamber 90 and into the chamber 106 of cylinder 102, moving the piston 104 to the right, from the point of view of Figure 1, so it returns to the original position shown.

[0025] At the same time, the piston rod 42 is forced downwardly into the reload chamber 46. This increases pressure in the reload chamber and keeps the ball 58 against valve seat 60 to prevent liquid from flowing back into the source chamber 70 through the passageway 52. The liquid in the reload chamber is thus forced upwardly into the piston rod 42 by raising valve member 43 off of valve seat 45. In this way, a portion of the liquid in reload chamber 46, which had flowed into the reload chamber from the source chamber as the piston was previously raised, moves from the reload chamber into the piston rod and refills the cylinder 26 above the piston 40 as the piston moves downwardly towards its lowermost position shown in Figure 1.

[0026] The piston 104 in the cylinder 102 is then pushed again to the left, from the point of view of Figure 1, and again raises the piston 40. A volume of liquid equal to the volume of liquid which moved into the piston rod 42 from the reload chamber 46, as the piston 40 previously moved downwards, is then discharged from passageway 32 as the piston 40 approaches its uppermost position and piston 102 approaches its position closest to the discharge end 100 of cylinder 102.

[0027] The cycles are then continued and, as may be readily understood, each time the piston 40 moves down and back up, it pumps a volume of liquid from the reload chamber 46, and ultimately from source chamber 70, equal to the difference in volume occupied by the piston rod 44 within the reload chamber 46, when the piston 40 is in the lowermost position as shown in Figure 1, less the volume it occupies within the reload chamber (if any) when the piston 40 has reached its uppermost position. The travel of the piston 40 is adjusted so that the piston rod remains within the aperture 48 at the uppermost limit of travel of the piston 40 and piston rod.

[0028] The pump apparatus described above is capable of pumping liquid from point 22 to point 32 as described above. Thus the apparatus is capable of pumping liquid against a significant hydraulic head, such as experienced in pumping water from the bottom of a mine, without requiring a pump with a high hydraulic head output. This is because liquid in column 92 acts upwardly against the bottom of the piston 40 and assists the movement of the piston 104 towards the left, from the point of view of Figure 1. When the piston 40 is moved downwardly by the weight of liquid in cylinder 26 above the piston, it moves the liquid in chamber 90 upwardly, increasing its hydraulic head and building up its potential energy. Thus a large portion of the energy lost as the piston 40 moved downwardly is recovered in potential energy represented by the liquid in column 92 extending to cylinder 102.

[0029] Thus it may be seen that the cylinder 102 should be placed as high as possible for the maximum recovery of the energy. It should be understood that the position of cylinder 102 could be different than shown in Figure 1. It could be, for example, oriented vertically. The terms “left” and “right” used above in relation to the cylinder, piston and piston rod are to assist in understanding the invention and are not intended to cover all possible orientations of the invention.

[0030] Figure 2 shows a pumping apparatus 20.1 which is generally similar to the apparatus shown in Figure 1 with like parts having like numbers with the addition of ".1". It is herein described only with respect to the differences between the two embodiments. Only the upper portion of the apparatus is shown, the reload chamber and source chamber being omitted because they are identical to the first embodiment. In this example passageway 34.1 is fitted with a one-way valve 120 which permits liquid to flow from chamber 90.1 into conduit 122, but prevents liquid from flowing in the opposite direction. The conduit 122 is connected to a receiver 124 which may be similar in structure to a hydraulic accumulator, for example, and is capable of storing pressurized hydraulic fluid. When the piston 40.1 is moved downwardly by the liquid in cylinder 26.1, it is forced into the receiver 124.

[0031] There is a hydraulic conduit 126 which connects the receiver to a centrifugal pump 128 which is connected to passageway 130 in the cylinder 26.1 below the piston 40.1 via a conduit 132. After the piston reaches its bottommost position, as shown in Figure 2, pump 128 is started to pump liquid from the receiver 124 into the chamber 90.1 to lift the piston 40.1. The fact that the liquid in the receiver 124 was pressurized during the previous downward movement of piston 40.1 reduces the work required from pump 128 to assist in raising the piston. Thus this apparatus operates in a manner analogous to the embodiment of Figure 1, but uses the receiver to store pressurized hydraulic fluid instead of utilizing a physical, vertical hydraulic head as in the previous embodiment. Furthermore a centrifugal pump 128 is employed instead of the piston pump comprising cylinder 102 and piston 104 of the previous embodiment. Otherwise this apparatus operates in a similar manner.

ANALYSIS OF PRESSURES AND FORCE BALANCE

[0032] Referring to Figures 1 through 5:

A_1 is the area of the top 29 of the transfer piston 40 which is the area of the transfer cylinder 26

A_2 is the area of the bottom of the piston rod 42

A_1 - A_2 is the area of the transfer piston in contact with the power fluid

S is the stroke length

P_1 is the pressure of the standing column

P_2 is the pressure of the working fluid during the power stroke

P_3 is the available head of the fluid to be pumped

P_4 is the pressure in the transfer chamber

P_5 is the pressure of the power fluid during the recovery stroke

P_c is the pressure created in the power cylinder 102 located at the same level as the standing column discharge 32

W is the weight of the piston

R is the resistance created by the seals

d is the density of water (0.036 lbs/in3)

A_c is the area of the Power Cylinder

S_c is the stroke of the Power Cylinder

H is the height of the standing column of water

d is the density of water

[0033] During the recovery stroke the transfer piston moves down, with valve member 43 open and valve 56 closed.

Downward Forces $F_d = P_1A_1 + W$

Upward Forces $F_u = P_2(A_1 - A_2) + P_4A_2 + R$

Net force $F = F_d - F_u = P_1A_1 + W - P_2(A_1 - A_2) - P_4A_2 - R$

If we assume:

$P_1 = 45$ psig, approximately 100 feet of water, and $A_1 = 8$ in^2,

$P_1A_1 = 45 \times 8 = 360$ lbs

- a piston weight of 2 lbs (approximately 8 in^3 of steel)
- a seal resistance 20 lbs

$P_4 = P_1$ and therefore $P_4A_2 = P_1A_2$

$$F = P_1A_1 - P_1A_2 - P_5(A_1 - A_2) - R$$

$$F = P_1(A_1 - A_2) - P_5(A_1 - A_2) - R = (P_1 - P_5)(A_1 - A_2) - R$$

For this to be a net downward force, P_5 must be less than P_1. The area that P_1 operates on is $(A_1 - A_2)$.

[0034] During the power stroke the transfer piston moves up and valve member 43 closed.

Downward forces $F_d = P_1A_1 + W + R$

Upward forces $F_u = P_2(A_1 - A_2) + P_4A_2$

Net force= $F = F_u - F_d = P_2(A_1 - A_2) + P_4A_2 - P_1A_1 - W - R$

$P_4 = P_3$. If we assume $P_3 << P_1$ or P_2, we can ignore P_4A_2.

As for the recovery stroke we can ignore W.

$$F = P_2(A_1 - A_2) - P_1A_1 - R$$

[0035] Efficiency

Work in during the recovery stroke

$P_5 = P_1 - P_c$ where P_c is the pressure created in the power cylinder located at the same level as the standing column discharge.

Work done at the power cylinder

$W_i = P_c A_c S_c$,

$A_c S_c$ is the volume of power fluid moved per stroke = $(A_1 - A_2)S$

$W_i = P_c(A_1 - A_2)S$,

For an example, $P_c = 14$ psig, $A_1 = 8\ \text{in}^2{}_1$ $A_2 = 4\ \text{in}^2{}_1$ and $S = 12$ in

$W_1 = 14(8 - 4)12 = 672$ in lbs (56 ft lbs) plus R x S 20 x 12 = 240 in lbs.

$A_2 / A_1 = 0.5$

Work in during the Power Stroke

$P_2 = P_1 + P_c$. In order to create an acceleration of "a" times g (32.2 ft/sec^2) in the standing column, the net force must be "a" times the weight of the standing column.

$F = P_2(A_1 - A_2) - P_1A_1 - R = aHA_1d = aP_1A_1$

$(P_1 + P_c)(A_1 - A_2) - P_1A_1 - R = aP_1A_1$

$\mathbf{P_1A_1} - P_1A_2 + P_c A_1 - P_cA_2 - \mathbf{P_1A_1} - R = aP_1A_1$. The bold terms cancel.

$P_c(A_1 - A_2) = aP_1A_1 + P_1A_2 + R$

$$P_c = \frac{P_1(a A_1 + A_2)}{(A_1 - A_2)} + \frac{R}{(A_1 - A_2)}$$

For a head of 100 feet, $P_1 = 43.3$ psig, and a = 1 g, R = 20 lbs.

$$P_c = \frac{43.3(1x8+4)}{4} + \frac{20}{4} = 130 + 5 = 135 \text{ psig}$$

Work In at the power cylinder

$W_i = P_c(A_1 - A_2)S = 135 \text{ x } 4 \text{ x } 12 = 6480$ in lbs

Work Output

The amount of water lifted is $SA_2d = 12 \text{ x } 4 \text{ x } 0.036 = 1.73$ lbs it is raised 1200 inches

$W_0 = 1/73 \text{ x } 1200 = 2070$ in lbs = 173 ft lbs

Efficiency based on A_2/A_1 ratio of 0.5

$E = W_0/W_1 = 2070/(6480 + 672 + 240) = 28.0\%$

By examining the above formula for P_c one can see how changing the acceleration and the ratio of A_2/A_1 affects the pressure necessary to drive the pump. For example:

$A_2/A_1 = 0.8$ or in the example A_2 would now = 6.4 sq. in. and a = 0.25 g

$$P_c = \frac{P_1(a\,A_1 + A_2)}{(A_1 - A_2)} + \frac{R}{(A_1 - A_2)}$$

$$P_c = \frac{43.3(.25x8+6.4)}{1.6} + \frac{20}{1.6} = 227 + 12.5 = 239.5 \text{ psig}$$

or using a lower A_2/A_1 ratio – say 0.25, now $A_2 = 2$ and leaving acceleration at 0.25g

$$P_c = \frac{P_1(a\,A_1 + A_2)}{(A_1 - A_2)} + \frac{R}{(A_1 - A_2)}$$

$$P_c = \frac{43.3(.25x8+2)}{6} + \frac{20}{6} = 28 + 3.33 = 31.33 \text{ psig}$$

We are now moving a volume of water up 100 feet in our example by adding 31.33 psi (72.37 ft.) of head to the power column.

DYNAMIC ANALYSIS OF THE ORIGINAL CONCEPT

[0036] Recovery Stroke

Continuing with the same example the net force on the Standing Column 26 is:

$F = P_c(A_1 - A_2) - R = 14(8 - 4) - 20 = 36$ lbs

The mass of the Standing Column is

1200 x 8 x 0.036= 346 lbs.

The acceleration is

$36/346 = 0.10\ g = 3.22\ ft/sec^2$

The time required to complete the stroke

$D = \frac{at^2}{2}$: D = S in feet = 1 foot;

$t = (2S/a)^{0.5} = (2/3.22)^{0.5} = 0.79$ seconds

[0037] Power Stroke

The acceleration was defined as 1 g or 32.2 ft/sec^2.

$t = (2/32.2)^{0.5} = 0.25$ seconds.

The complete stroke will take 0.79 + 0.25 = 1.03 seconds

[0038] The above analysis of pressures and force can be manipulated using different ratios of $A_2/A1$, P_2/P_1 and acceleration "a".

[0039] Attached as Figure 3 is a performance curve for the pressure head concept showing the efficiency against the ratio A_2/A_1. Also included as Table 1 are the calculations from which Figure 3 is drawn showing the absolute numeric variations as parameters are changed.

[0040] Table 1

Efficiency vs A2/A1						
A2/A1=	0.4	0.5	0.6	0.7	0.8	0.82
P2/P1						
1.5	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
1.8	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
2.0	41.4%	0.0%	0.0%	0.0%	0.0%	0.0%
2.5	31.6%	45.7%	0.0%	0.0%	0.0%	0.0%
3.0	25.5%	37.2%	53.3%	0.0%	0.0%	0.0%
4.0	18.5%	27.1%	39.3%	59.1%	0.0%	0.0%
5.0	14.5%	21.3%	31.2%	47.1%	0.0%	0.0%
7.5	9.4%	13.9%	20.5%	31.3%	53.7%	61.1%
10	6.9%	10.3%	15.3%	23.5%	40.2%	45.8%
Optimum	26.6%	315.%	36.0%	40.7%	46.3%	47.5%
P5/P1, req	0.39	0.31	0.185	0.05	0.05	0.05
Rec Acc ft/sec2	8.04	8.01	8.04	7.21	4.21	3.61
P2/P1 opt	2.9	3.48	4.35	5.79	8.69	9.65

[0041] For the pressure head concept, the curves demonstrate that a pump could approach an efficiency of up to 61% if used in applications where a very high pressure head is available and the power water can be discharged at a very low level, both compared to the height of the standing column. Efficient pump designs have a high A_2/A_1 ratio indicating that the volume of water discharged from the standing column is greater than the volume of water used on the power side of the transfer piston. This feature indicates that the pump may be attractive in lifting water from a well or de-watering a mine as long as there is a convenient source of suitable power water; i.e. compatible with the water to be lifted and having a very high head. As previously discussed, a pressure head pump could be attractive in some run-of-the-river hydro applications if a suitable source of power water is convenient.

[0042] For the power cylinder concept, the curves indicate that the higher the A_2/A_1 ratio the more efficient the pump, and the lower the accelerations the more efficient the pump.

[0043] Efficient pressure head concept pumps move a greater volume of process water per stroke than the volume of power water required. This again is a direct result of the high ratios of A_2/A_1. This means that the power water could be released to join the process water and still allow effective pumping to occur. Conversely, pumps with low ratios of A_2/A_1 but with a large amount of power water and a lower head can move smaller amounts of process water up greater heights. They will expend more power water than the process water they move. This process is similar to the classic hydraulic ram principle where a large amount of fluid at a low pressure head is used to transfer a small amount of fluid up a higher elevation.

[0044] A different embodiment of the pump utilizes a bladder similar to a pressure tank in a water system or a packer similar to a drill hole packer that houses the water in the power cylinder that is pressurized by air or hydraulic pressure and then the pressure lowered and again repressurized. This allows the use of the pump without expending the power fluid.

ANALYSIS

[0045] Figure 5 shows the two main embodiments of the pump. Figure 5A describes the pressure head concept showing how the liquid, generally water, stored at a higher elevation 83 supplies excess pressure for the power stroke 85 and reduced pressure 87 when point 89 is used for the power fluid release. Figure 5B shows the power cylinder concept where the excess pressure is generated by the power cylinder 102 and the recovery stroke is augmented by the creation of a vacuum when piston 104 is withdrawn from the column of power fluid.

PERFORMANCE CURVES

Pressure Head Concept

[0046] Referring to Table 1, the valves were manipulated to calculate the efficiency of various pressure head arrangements. The manipulation required:

- setting various ratios of A_2/A_1 from 0.4 to 0.82 then, for each of the ratios,

- calculating the recovery stroke performance for various ratios of P_5/P_1 (the height of the power water release compared to the standing column height),

- "optimising" P_5/P_1 to obtain a recovery stroke acceleration of 8 ft/sec^2, if possible,

- using the "optimised" results from the recovery stroke calculations as input for the power stroke calculations,

- calculating the power stroke performance for various ratios of P_2/P_1 (the height of the power water source compared to the standing column height),

- "optimising" P_2/P_1 was to obtain a power stroke acceleration of 8ft/sec^2,

- transferring the calculated efficiencies to another spreadsheet along with the "optimised" P_5/P_1 and P_2/P_1 ratios and the recovery stroke acceleration,

- using the calculated efficiencies to plot a graph of efficiency vs A_2/A_1 for the most significant ratios of P_2/P_1.

[0047] The results indicated that high ratios of A_2/A_1 result in higher efficiency and low acceleration. The results also indicate that a low ratio of P_5/P_1 is required to create reasonable recovery stroke acceleration.

[0048] Referring to Table I, performance data for the ratio $A_2/A_1 = 0.82$ is shown which indicates that an efficiency of 61% could be achieved if a power stroke acceleration of 8 ft.sec 2 (0.25g) is considered acceptable. The recovery stroke acceleration will be around 4 ft/sec2 with this design.

[0049] What is not immediately apparent is that when the A_2/A_1 ratio is high, the amount of power water released per stroke is much less than the amount of process water lifted per stroke. The amount of process water lifted per stroke is A_2S and the amount of power water released per stroke is $(A_2 - A_1)S$.

[0050] When $A_2/A_1 = 0.8$:

$$(A_2 - A_1) = A_1 - 0.8A_1 = 0.2A_1$$

and the amount of power water released per stroke is

$$(A_2 - A_1)S = 0.2\ A_1S$$

and $A_2 = 0.8A_1$:

therefore the amount of process water lifted is

$A_2S = 0.8\ A_1S$

or four times the amount of power water released.

This means that the power water could be released into the process water and the pump will still pump a net of $(0.8 - 0.2)A_1S = 0.6A_1S$ per stroke.

Power Cylinder Concept

[0051] Values were manipulated to calculate the efficiency for various power cylinder arrangements. The manipulation required is:

- setting various ratios of A_2/A_1; from 0.4 to 0.82, then, for each of the ratios,

- setting the pressure in the power cylinder (P_c) during the recovery stroke ,

- calculating the recovery stroke performance for various ratios of H_p/H_1 (the height of the pump compared to the height of the standing column),
- "optimising" H_p/H_1 to obtain a recovery stroke acceleration of 8ft/sec^2, if possible,

- using the "optimised" results from the recovery stroke calculations as input for the power stroke calculations,

- calculating the power stroke performance for various ratios of P_2/P_1,

- "optimising" P_2/P_1 to obtain a power stroke acceleration of 8 ft /sec^2,

- transferring the calculated efficiencies to another spreadsheet along with the "optimised" H_p/H_1 and P_2/P_1 ratios and the recovery stroke acceleration,

- using the calculated efficiencies to plot a graph of efficiency vs A_2/A_1 for the most significant ratios of P_2/P_1.

[0052] The results indicate that high ratios of A_2/A_1 result in higher efficiency and lower ratios allow moving fluid to higher heads but using more process water or a larger power column if contained in a bladder or packer.

ATTRACTIVE APPLICATIONS

[0053] For the concept pump to be reasonably efficient, the ratio A_2/A_1 must be high. For this sort of pump to have a reasonable recovery stroke acceleration the power water in a pressure head style pump must be released very low relative to the height of the standing column. For this sort of pump to have a reasonable power stroke acceleration the power column must be very tall relative to the standing column. These features indicate that the pump would be attractive in applications where there is a source of power water at an elevation much higher than the standing column height. It must also be possible to release the power water at a very low elevation relative to the height of the power column in a pressure head style pump.

- the previously discussed run-of-the-river hydro booster application could fit these requirements, Analysis shows that this application allows the recovery of more than 55% of the energy of a high elevation tributary if it is channeled to a pressure head style pump placed at the bottom. The pump lifts almost five times as much water as is used to power the pump if the water is lifted $1/10^{th}$ of the height of the power head. The water is then recycled through the turbine at the bottom.

- using the pump to de-water a mine could also be attractive,

- raising water from a well could be attractive.

- raising water to a reservoir or to a higher elevation (pressure) could also be attractive